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LUNAR STRUCTURES AS DEDUCED FROM MUONG NONG TEKTITES

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ABSTRACT

From previous work, it is generally believed that tektites are derived either from terrestrial sedimentary rocks or from the moon. The Muong Nong tektites contain angular voids, an indication that they have never been completely melted. Microprobe studies of the voids indicate that they are chemically homogeneous, which seems to rule out the possibility of the tektites' having a terrestrial sedimentary origin and to indicate that they are from fragmental glass and of lunar origin. This conclusion is reinforced by Walter's discovery of coesite in tektites; it is interpreted in the light of theoretical studies of lunar ash flows, and the result is compared with the known lunar topography. Finally, the possibility that the lunar red spots may be lightening-generated during a small ash flow is noted.

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INTRODUCTION

One avenue toward knowledge of the moon's surface is undoubtedly furnished by the fragments of that surface which must fall on the earth. Because it has no atmosphere, the moon is exposed to bombardment by particles having velocities of up to nearly 80 kilometers per second. Laboratory experiments show that under bombardment at these velocities ejecta will be produced which will travel at speeds in excess of the escape velocity from the moon (2.3 kilometers per second) and which, in the absence of an atmosphere, will leave the moon and eventually, at least in part, find their way to the earth.

Since the time of Dutch mining engineer Verbeek (Reference 1), it has been suspected that tektites are among these ejecta from the moon. The idea has been advanced in recent years by the discovery of Chao, Adler, et al. (References 2 and 3) that the nickel-iron spherules which are the hallmark of impact in some terrestrial glasses are also present in tektites. This theory has also been advanced by the work of Chapman and Larson (Reference 4) and Adams and Huffaker (Reference 5), who have deduced from the forms of the australites that the bodies arrived in the earth's atmosphere with trajectories which are inconsistent with a terrestrial origin but are not inconsistent with an origin from the moon.

DESCRIPTION OF MUONG NONG TEKTITES

Recently, important new light on the problem has been shed by the study of tektites of the Muong Nong type. This name was given by Barnes (Reference 6) to a class of tektites, found chiefly in Thailand and Indo-China, which have the characteristic that the internal structure is layered. The layering is of somewhat the same nature as the contorted, fluidal structure seen in almost all tektites, but in the Muong Nong material the structure is arranged in parallel layers and is accompanied by a remarkable appearance within each layer to which Barnes has given the name of "shimmering." The Muong Nong materials have been clearly shown by analysis by Barnes

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and Pitakpaivan (Reference 7) to be chemically identical with the other tektites (to which Barnes has, for contrast, given the appropriate name "splash-form tektites") except for a minor difference in a state of oxidation of the iron. The resemblance is close enough so that we may be sure not only that the Muong Nong materials are genuinely tektites but even that they belong to the Far Eastern strewn field.

Barnes (Reference 8) further found that the splash-form tektites, when examined as whole bodies between crossed nicols, show a pattern of strain birefringence which indicates that each one cooled as a unit. Since the Muong Nong material shows no such overall strain pattern the Muong Nong tektites may be fragments of larger bodies; this idea is also suggested by the fact that Muong Nong tektites are generally found in large associations (Reference 9) weighing tens of kilograms and covering a few tens of square meters. Further support for this theory comes from the external shapes of the Muong Nong tektites, which are generally chunky fragments and contrast sharply in shape with the splash-form tektites. The latter, when complete, normally have the forms found in liquid rotating masses: spheres, spheroids, rods, dumbbells, tears, and so forth.

There is every reason to subscribe, therefore, to Barnes's contention that, in a fundamental way the Muong Nong materials are more primitive than other tektites and are very close to the original material.

TESTS OF TEKTITE ORIGIN

Recently, Barnes (Reference 10) drew attention to the presence of angular voids in some of the Muong Nong tektites, particularly in those from Kan Luang Dong. His photograph is shown in Figure 1. The voids appear dark because of reflections from the walls of cavities. The significance of the angular voids was pointed out by Barnes, who remarked that they clearly indicated that these tektites had once been some kind of clastic, that is, fragmental, material whose grains had been incompletely welded together. The angular voids, therefore, represent the spaces between grains. Barnes pointed out that this implied that these tektites had never been thoroughly melted since it is well known that voids in a liquid, even a viscous liquid, are spherical or ellipsoidal.

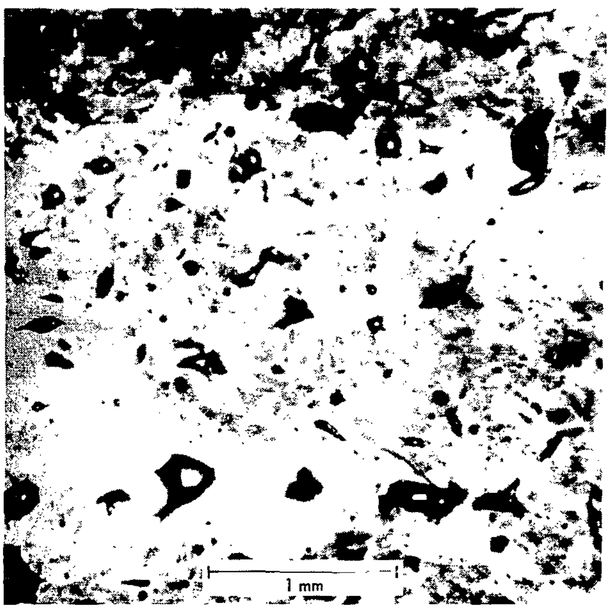

Figure 1—Angular bubbles observed in a Muong Nong tektite from Kan Luang Dong, courtesy of V. Barnes. The black marks are voids.

Now this at once opened the way for a decisive test of the theories of the origin of tektites. If tektites are fused sandstone as claimed by Barnes himself (Reference 11), by H. C. Urey (Reference 12), and by S. R. Taylor

(Reference 13), then in the Kan Luang Dong tektites we would expect to find the minerals which normally compose a sandstone (Reference 14, p. 318), namely, quartz, chert, feldspar, mica, clay, and other minerals existing as separate chemical entities. It is, of course, entirely possible that each of these minerals might have been converted to a glassy form; for instance, the quartz may have been converted to lechatelierite or the feldspar, to maskelynite as a result of shock. But these materials should, nevertheless, remain chemically distinct. From the appearance of Figure 1, it is clear that the grain size of the source material was on the order of 50μ. In Figure 2, we see an enlarged portion of a similar Muong Nong tektite from Phang Daeng. It is evident that this tektite is composed of separate pieces of material which were pressed together while soft. The region chosen contains two inclusions; these permit easy orientation in the subsequent figures. Actually, such inclusions cover no more than 15 percent of the area of this portion of this tektite.

In Figure 3, we see the results of a microprobe scan using the K_α line of potassium over the region between the two large spots of Figure 1. The uniform nature of the material is obvious. Remelted bits of feldspar would have shown up as bright spots. Figure 4 shows the results of the same type of scan with silicon; here the silica in the inclusions shows up. Figure 5 uses aluminum; it is uniform outside the black spots (in the inclusions, the voids have become filled with grinding compound, Al_2O_3, which thus forms a pattern complementary to the silicon). Figure 6 shows a similar pattern using calcium; a similar pattern using iron is too faint to reproduce.

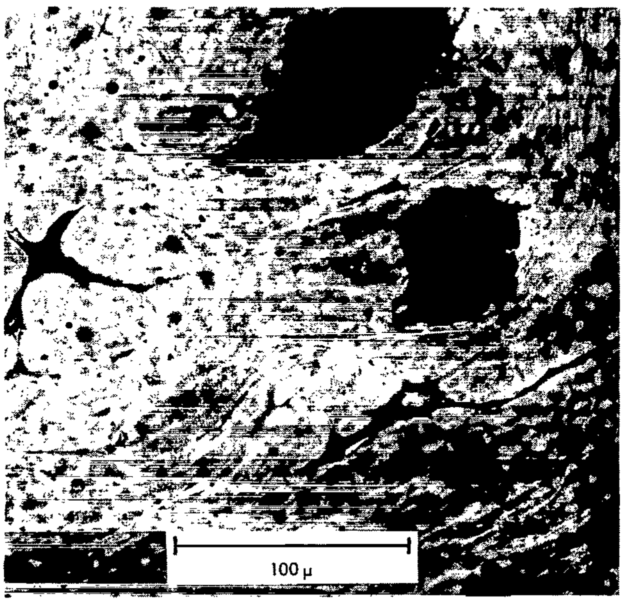

Figure 2—Microphotograph showing internal structure of a portion of a Muong Nong tektite from Phaeng Dang. The two large black spots are inclusions and the small, streaky black lines are voids between shard-like glass bodies. The voids do not extend through the section.

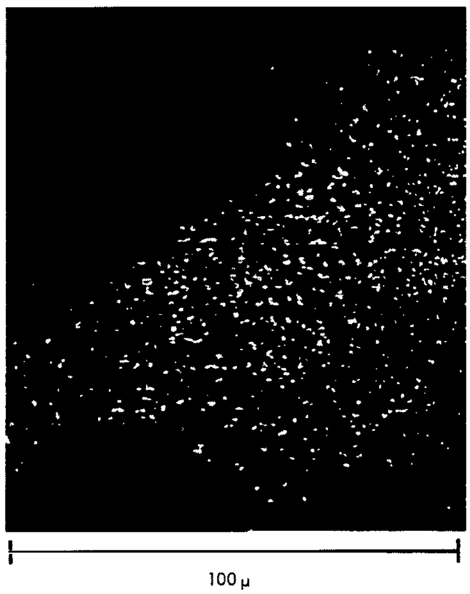

Figure 3—A portion of the region shown in Figure 2 in the line of the potassium K_α line prepared by microprobe scanning using X-ray fluorescence. The image is a reversal of that in Figure 2. Note the homogeneity of the material outside the black inclusions.

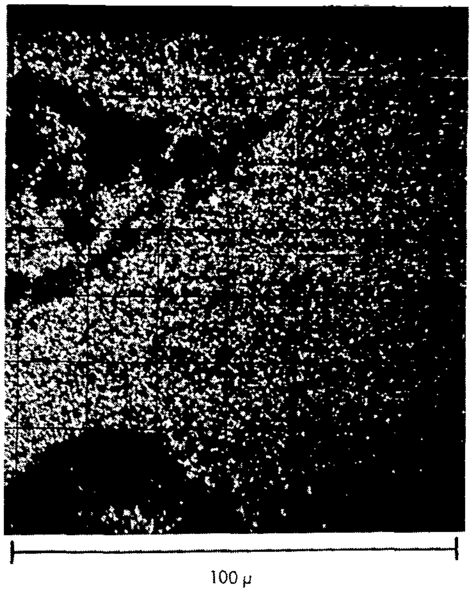

Figure 4—Microprobe scan for silicon of same region as that shown in Figure 3. A network appears in the spots because these are largely composed of vesicular SiO_2 (frothy lechatelierite).

Figure 5—Microprobe scan for aluminum of same region as that shown in Figure 3. The same as Figure 3 using aluminum. Note that the voids in the silica have become blocked up with alumina from the grinding powder.

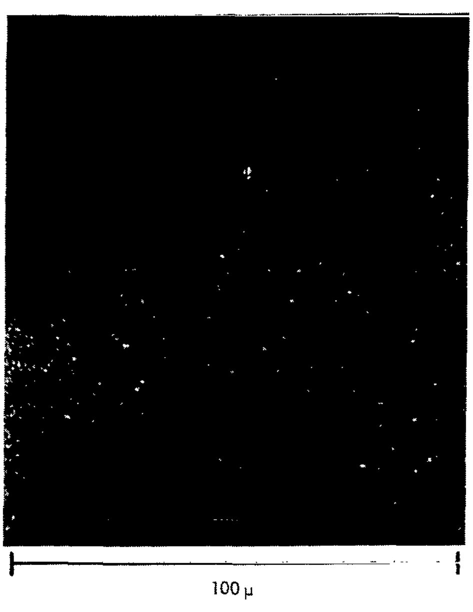

Figure 6—The same as Figure 3 using calcium.

For comparison, the same techniques were employed on a chemically similar terrestrial specimen (from Texas) kindly supplied by E. A. King, Jr. It is a portion of a tuffaceous sandstone or siltstone baked by natural fires in an underlying lignite bed. The chemical composition is given by King (Reference 15); King pointed out that it resembles the composition of a tektite (in particular, a bediasite).

In Figure 7 are similar cathode ray displays for potassium, iron, silicon, and aluminum on the Texas siltstone. The figures are in each case 90μ across. It is evident that the microprobe has more than enough resolution to show the heterogeneous character of this material if the grain size is of the order of 50 microns.

We see that the Kan Luang Dong material is chemically homogeneous and unlike fused soil.

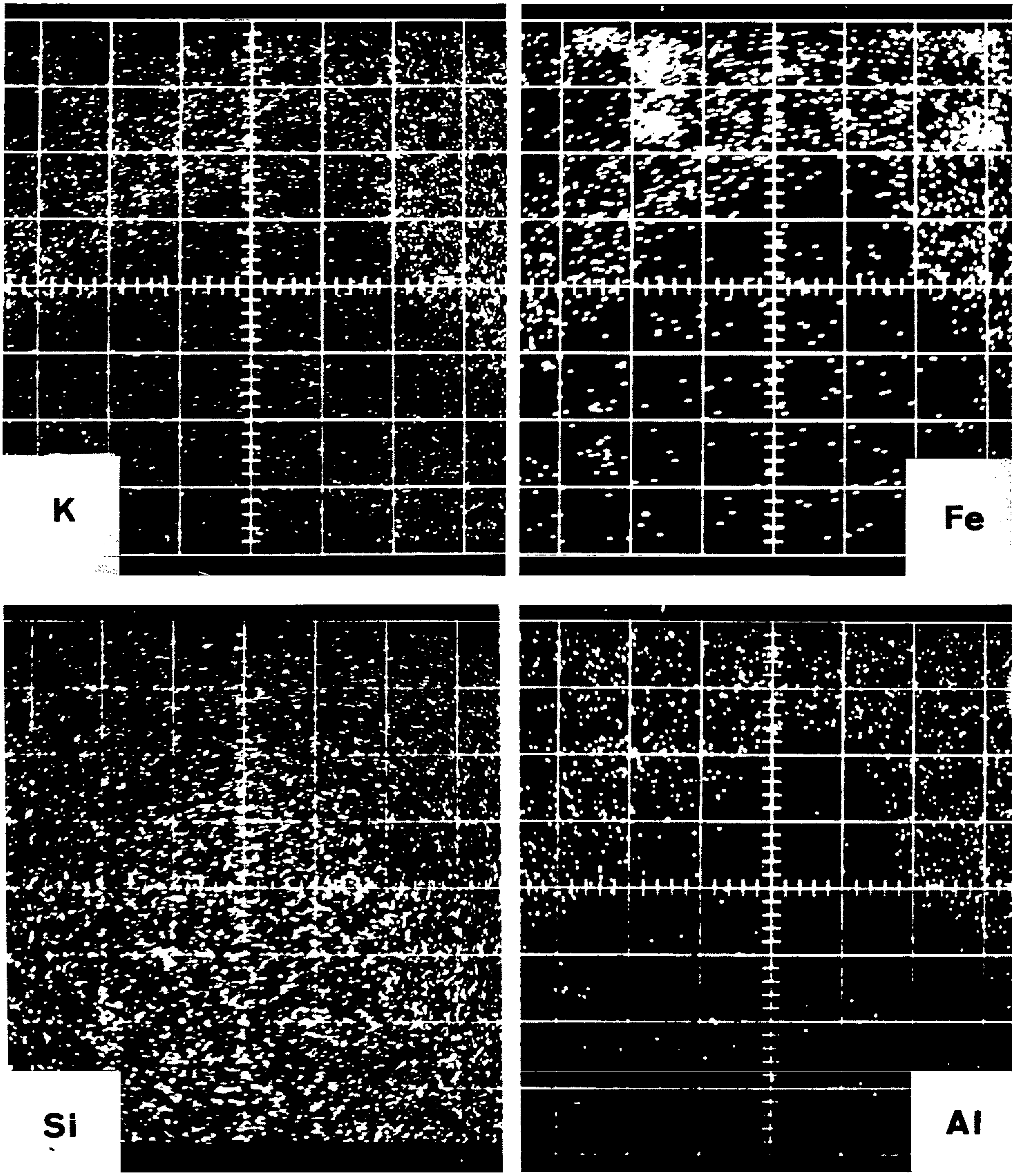

Figure 7—Microprobe scans for elements potassium, iron, silicon, and aluminum in a sample of Texas siltstone. Note the inhomogeneity of the siltstone with the tektite. Each figure is 90μ across.

COESITE IN TEKTITES

While these studies were going on, Dr. L. Walter at Goddard (Reference 16) made what is perhaps the most fundamental discovery in the tektite problem. He examined some small inclusions to which Barnes has given the name "frothy lechatelierite" which are found in the Muong Nong material and which, in the specimens he examined, formed perhaps 1 percent or less of the total volume. Walter discovered that the brown central portions of these inclusions contain coesite, which is a high-pressure form of silica that is unstable at ordinary temperatures. Since the pioneer work of Chao, Madsden, and Shoemaker (Reference 17), the presence of coesite in a natural rock has been thought to be an indicator of impact by a meteorite. This interpretation is a very natural one in the present case because of the already mentioned existence of the nickel-iron spherules. It constitutes a welcome confirmation and eliminates for good the arguments of some doubters who thought that perhaps the nickel-iron spherules were the result of some process of chemical reduction in the glass.

But the coesite has a more fundamental significance because of its instability and especially its tendency to turn into cristobalite. The presence of coesite and the absence of cristobalite constitutes, in Walter's phrase, a "seal" which guarantees that the material has not been substantially altered since the impact. The kind of heating which would be required to convert a sandstone, for example, into the kind of glass which we observe in the Muong Nong material would convert some of the coesite to cristobalite. In Figure 8, we show a theoretical calculation of the rate at which a grain of tektite glass would diffuse into a glass matrix compared with some measures by Dachille et al. (Reference 18) of the rate at which coesite disappears. A single observation by Barnes that lechatelierite particles in bediasites are half gone in 1/2 hour at 1600°C is plotted as a cross. It is clear that we are not likely to get rid of the quartz grains without producing cristobalite.

This theoretical conclusion is fully substantiated by experiment. The problem of dissolving quartz grains in a glassy melt is one of the fundamental problems of glassmaking. It is known to be a difficult problem, especially in a viscous melt, and one which requires hours, if not days. Recently, Corning Glass Works prepared an artificial tektite glass; it is our understanding that they employed a temperature of 1900°C for 16 hours. By contrast, the maximum quench time permitted by the studies of Muong Nong coesite is about 10 seconds at 1700°. This conclusion is certainly what we would expect. The destruction of the coesite demands no more than the disordering of a crystal lattice while the dissolving of the quartz grains demands migration of the silica molecules through distances of tens of microns.

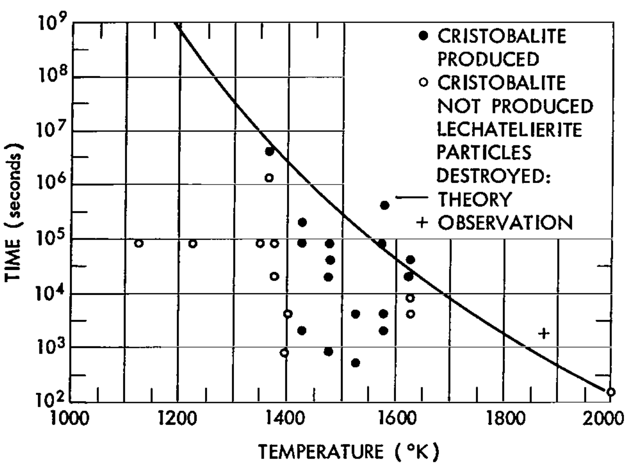

Figure 8—Production of cristobalite against destruction of lechatelierite particles.

In fact, this migration has not even begun, as can be seen by examination of the borders of these inclusions (Reference 16, p. 1029). The transition from tektite glass to silica glass takes place in a very short distance much smaller than the diameter of the particle.

TEKTITES DERIVED FROM GLASS FRAGMENTS

From the aforementioned data, Walter drew the vitally important conclusion that the Muong Nong material was glass or finely crystalline before the impact took place. This conclusion is, as Walter has pointed out, difficult to reconcile with the origin of tektites from terrestrial material. Glasses of tektite chemistry are not found at the surface of the earth. The kind of major changes which would be required to convert a terrestrial rhyolite into a tektite, are, if anything, more difficult to reconcile with the presence of coesite than the melting process which we have already discussed. It is highly probable that, as Taylor has pointed out (Reference 16), an impact by itself has little effect on the chemistry of the struck material and, in particular, is not enough to convert a rhyolite into a tektite glass. We are thus led to conclude that the impact took place on a glass whose composition was not that of these found on the earth.

What was the nature of the glass which formed the Muong Nong tektites? From the remarks of Barnes about the angular voids, we are led, in a logical way, to suppose that the glass consisted of some kind of fragmental, or clastic material. Clastic glass is called by geologists a tuff. Thus the Muong Nong material is a tuff.

In most specimens of Muong Nong material there are few voids. This could logically be explained if we imagined that the fragments have been welded together as sometimes happens with terrestrial tuff. If the material is tuffaceous and welded, then it is what we call a welded tuff.

It is possible to make direct comparisons between Muong Nong material and terrestrial welded tuff. The resemblance is close enough to interest and impress not only an outsider but also professional students of welded tuffs.

MECHANISM OF PRODUCTION OF LUNAR WELDED TUFFS

There is a chain of argument which says that if the tektites are not from the earth then they must be from the moon. The argument is based first on the lack of Al 26 (Reference 19), which should have been produced by primary cosmic ray bombardment if the tektites had been in space for a long time. It is also based on the distribution of tektites, which is best understood as the result of fallout from an orbiting satellite. It is extremely difficult to see how a body could get into a satellite orbit around the earth unless it were an impact fragment from the moon. In what remains, we shall therefore discuss the Muong Nong tektites as samples of the lunar surface.

On the earth, welded tuffs are normally produced by a process which is known as ash flow (Reference 20). An ash flow is a volcanic eruption in which the tiny ash particles, instead of floating downward through the cold air and arriving at the ground cold and rigid, are immersed in the hot gas and arrive at the final point of deposition still hot and plastic. Two modes of transport are possible. In some ash flows, such as the great explosion of Mont Pelée in 1902 (Reference 21), there is a great volume of gas and very little ash. The small amount of ash, nevertheless, provides coherence for the gas by impeding the spread of the gas molecules in all directions and provides weight for the gaseous mass. The mixture of gas and dust behaves like a fluid, moves toward the lowest point of the topography, and there settles out. Deposits of this kind on the earth are not normally welded and are relatively unimportant.

A second mode of transport may be called the dense phase. In the dense phase, we have mostly solids and very little gas. There is just enough gas to separate the particles from one another so that the friction is greatly reduced or disappears. The mass behaves like a liquid with a more or less definite upper surface and a density which is of the order of 1 or 1-1/2 grams per cubic centimeter. This pseudoliquid moves across the topography, finds a suitable bed, stops, and then collapses, first through the escape of gas from between the solid particles and then through the compression of the solid particles one on the other. The solid particles when emplaced are still at a temperature of 850°C, according to the estimates of Boyd (Reference 22). They are still plastic; welding can and does take place.

The application of these ideas to the moon might, at first sight, seem impossible since it might seem that in a hard vacuum the gas would immediately escape. It was first pointed out by Lyman Spitzer (Reference 23) that the escape of gas from particles in a vacuum is a much slower process than we would have thought. It is delayed, in part, by the charging up of the solid particles, at the expense of the gas. The resulting difference in charge means that very large voltages will develop if there is any significant separation of solids from gas. The internal particles, therefore, in seeking to escape from the gas will encounter not only the solid particles but the charged gas molecules as obstructions.

A physical analysis by O'Keefe and Adams (Reference 24) shows that the behavior of a lunar flow of ash in the dense phase is not unlike that in the terrestrial fluidized material. The differences between the lunar and the terrestrial case mostly favor the process of fluidization. The lower gravity means that the solid particles are more easily carried. It also means that as we go down through the lunar ash flow the pressure increases less rapidly than in a terrestrial flow. Hence the density also increases less rapidly. Now it is a paradox of the kinetic theory of gases that the viscosity of a gas is independent of its density. Since the gas viscosity is the principal agent responsible for supporting the particles, it follows that a low-density gas can support as much solid matter as one of higher density. There is, of course, a limit: When the mean free path becomes of the same length as the width of the passages between solid particles, the viscosity and thus the supporting power of the gas breaks down; but for ordinary levels of density the lower pressures of the moon and the resulting lower densities are pure gain. That, in conjunction with the lower weight of the particles, means that a given amount of gas will fluidize about 30 times as much solid matter on the moon as it will on the earth.

As we approach the top of the densely fluidized layer, the diminishing pressure and diminishing density must be compensated for by an increasing gas velocity in order to carry off the flux of gas which has been generated below. Hence the gas density cannot go to zero; if it did, the velocity would have to go to infinity. The limit is reached when the upward velocity of the gas exceeds the terminal velocity of the small solid particles. They are then carried upward from the dense phase into the dilute phase which we previously mentioned. Because of the absence of a lunar atmosphere, we will always have a dilute phase above a lunar ash flow; calculations seem to show that this dilute phase may carry a substantial amount of the material.

RECONCILIATION OF THEORY WITH LUNAR TOPOGRAPHY

A lunar ash flow provides a fairly good explanation for the softening which has been observed in the outlines of lunar craters from the Ranger photographs. This softening is often attributed to erosion but there are powerful numerical reasons for thinking that erosion is not responsible. There appears to be at least 20 or 30 meters of deposit even over craters which must be relatively recent; but, from considerations of the radiation darkening of the moon (Reference 25), it appears unlikely that the moon's surface is being eroded at a rate greater than about 1 meter per billion years. It is of no use to say that the erosion rate might have been more rapid in ancient times, because the cratering rate would also have been greater in those ancient times.

What we observe on the Ranger photographs is that there have been 20 or 30 meters of softening *since the majority of craters in the 50- to 500-meter diameter range were formed.* It is quite logical to explain this softening in terms of a layer some 20 or 30 meters thick spread over the existing craters. Quite possibly this layer is not unique; no doubt there were a number of layers, as, in general, there are a number of separate flows in any large deposit of welded tuff. The important point is that the flows had a definite and limited thickness so that large craters in this region retained their original shape while the middle-sized craters were softened or even partly destroyed. Craters below 50 meters in diameter were, it appears, completely obliterated by the flow. You will see that this implies that the flow was of the type which we have called a dilute flow; that is to say, it was a dusty gas. Had it been a dense flow of the nature of liquid, then all holes, however deep, would have been filled by the liquid as long as there was enough to cover the highlands. If, however, we are dealing with a pseudo-gas, then the amounts of solid material per square centimeter would be approximately the same over the smaller terrain features. The amount of gas in a crater 200 or 300 meters deep would be only a few times the amount on the level ground if the scale height in the gas were a few hundred meters as calculated by Adams and O'Keefe (Reference 24).

After the deposit of the ash, new craters were formed which were naturally unaffected by it. We believe these are the smaller craters on the lunar surface simply because there are always more little craters than big ones, and the little craters which occurred before the ash flow have been effaced. It is a striking phenomenon in the study of the Ranger photographs that craters a few meters in diameter look more like the largest craters of more than a kilometer in diameter than they look like the medium-sized craters having a diameter of several hundred meters. The large craters were too big to be smoothed; the little onces, too recent.

RELATION TO RED SPOTS

In connection with ash flows, we should like to draw attention to the interesting possibility that the red spots on the moon, which have been observed by Kozyrev (References 26 and 27), Greenacre (Reference 28), and others, may be manifestations of a sort of lunar lightning. There are two observations of the spectra of these spots, both by Kozyrev. The first of these (Reference 26) indicated a spectrum which might be explained by C_2. The second (Reference 27) was considerably more detailed and indicated the presence of the molecule H_2. The latter is in all ways more plausible, especially because it gives rise to a red illumination. Water is the principal gas which is emitted in volcanic outbursts. In his 1963 paper, Kozyrev stated that the source of the H_2 could not be water since this would disassociate into H and OH, and he did not observe the lines of H. On the other hand, the excitation of water vapor is one of the standard methods of producing the H_2 spectrum. The OH bands are not obvious in the visible spectrum. It appears possible, in spite of the absence of atomic hydrogen lines and provided that we can find a suitable method of excitation, that the H_2 is due to water vapor.

On the other hand, there is a serious problem arising from the fact that the bands of the H_2 molecule which are visible in this spectrum come from levels which are 15 volts above the ground. The production of such a large amount of high-energy quanta is a genuine puzzle. The difficulty can perhaps best be seen by keeping in mind that the red spots have been seen on the bright portion of the moon's surface. It follows that, over the areas on which they are seen, the amount of light coming from the red spots was a substantial fraction of the total amount of sunlight which was being reflected by the moon at these points. It is known that the reflection efficiency of the moon is on the order of 9 percent. The energy supplied by the sun is on the order of 1.3 million ergs/sec/cm^2. The light reflected by the moon is therefore perhaps 100,000 ergs/sec/cm^2 and the light supplied by the red spots would have to be a substantial fraction of this. The total amount of radiation supplied by the sun in the ultraviolet region where 15 volts quanta are available is of the order of 10 ergs/cm^2/sec. The energy supplied by particles in the form of the solar wind is likewise of the order of 1 or 2 ergs/cm^2/sec. Thus the sun is utterly incapable of supplying the necessary energy. If, however, we suppose that the source of the energy is some kind of volcanic outburst, then it is obvious from terrestrial experience that the energy flux may greatly exceed the flux from the light of the sun. In a terrestrial volcanic outburst, a portion of the energy goes into lightning through mechanisms which are interpreted as static electricity but whose precise nature is not known. It turns out that whenever a suspension of small solid particles is produced in a gas we are very likely to have manifestations of static electricity. Examples, in addition to thunder storms and volcanic lightning, are the lightning associated with dust storms and the manifestations of static electricity in dusty factories.

It is perhaps significant that the observations of the red spots are associated with regions which appear to exhibit contemporary volcanism. These morphological intimations are so strong that Mrs. Cameron (Reference 29) predicted the appearance of red spots near the Cobra head in advance of Greenacre's report. Near Alphonsus, the Ranger IX photographs show plainly that recent volcanism has been at work.

CONCLUDING REMARK

It is suggested that the hypothesis of ash flow processes on the moon provides at the same time a reasonable explanation of the structure of the Muong Nong tektites, the morphology of some lunar craters, and the observations of lunar red spots.

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REFERENCES

1. Verbeek, R. D. M., "Glaskogels van Billiton," *Jaarb. Mijnwesen in Ned. Indië,* 1897:235-272, 1897.

2. Chao, E. C. T., Adler, I., Dwornik, E. J., and Littler, J., "Metallic Spherules in Tektites from Isabela, Philippine Islands," *Science,* 135:97-98.

3. Chao, E. C. T., Adler, I., Dwornik, E. J., and Littler, J., "New Data on the Nickel-Iron Spherules from Southeast Asian Tektites and Their Implications," *Geochim. et. Cosmochim. Acta,* 28:971-980, 1962.

4. Chapman, D. R., and Larson, H. K., "On the Lunar Origin of Tektites," *J. Geophys. Res.,* 68:4305-4358, 1963.

5. Adams, E. W., and Huffaker, R. M., "Parent Body Hypothesis for Origin of Tektites," *Nature,* 195:681-684, 1962.

6. Barnes, V., "A Worldwide Geological Investigation of Tektites," *GeoTimes,* 6(38):8-12, 1961.

7. Barnes, V., and Pitakpaivan, K., "Origin of Indochinite Tektites," *Proc. Nat. Acad. Sci.,* 48:947-855, 1962.

8. Barnes, V., "Tektites," *Scientific America,* 205(5):58-65, 1961.

9. Barnes, V., "Tektite Strewn Fields," *Tektites,* ed. by J. A. O'Keefe, Chicago: Univ. of Chicago Press, 25-50, 1963.

10. Barnes, V., "Terrestrial Implication of Layering, Bubble Shape and Minerals Along Faults in Tektite Origin," *Geochim. et Cosmochim. Acta,* 28:1267-1271, 1964.

11. Barnes, V., "Properties of Tektites Pertinent to Their Origin," *Geochim. et Cosmochim. Acta,* 14:267-278, 1958.

12. Urey, H. C., "Chemical Composition of Tektites," *Nature,* 183:1114, 1959.

13. Taylor, S. R., "Tektites: Origin of Parent Material," *Science,* 149:658-659, 1965.

14. Pettijohn, F. J., "Sedimentary Rocks," Second edition, New York: Harper and Brothers, 1957.

15. King, Elbert A., "Possible Relation of Tuff in the Jackson Group (Eocene) to Bediasites," *Nature*, 196:569-570, 1962.

16. Walter, L. S., "Coesite Discovered in Tektites," *Science*, 147:1029-1032, 1965.

17. Chao, E. C. T., Shoemaker, E. M., and Madsden, B. M., "First Natural Occurrence of Coesite," *Science*, 132:220-222, 1960.

18. Dachille, F., Zeto, R. J., and Roy, R., "Coesite and Stichovite: Stepwise Reversal Transformations," *Science*, 140:991-993, 1963.

19. Viste, E., and Anders, E., "Cosmic-Ray Exposure History of Tektites," *J. Geophys. Res.*, 67:2913-2919, 1962.

20. Ross, C. S., and Smith, R. L., "Ash Flow Tuffs, Their Origin, Geologic Relations and Identification," Professional Paper, 366, *Geological Survey*, Gov't Printing Office, Washington, D. C., 1961.

21. Lacroix, A.: La Montagne Pelée et ses Eruptions," Paris: Masson et Cie., 1904.

22. Boyd, F. R., "Welded Tuffs of the Rhyolite Plateau, Yellowstone Park, Wyoming," *Bull. Geological Soc. of America*, 72:387-426, 1961.

23. Spitzer, L., "The Dynamics of the Interstellar Medium II. Radiation Pressure," *Astrophys. J.*, 94(2):232-244, 1941.

24. O'Keefe, John A., and Adams, E. W., "Tektite Structure and Lunar Ash Flows, *J. Geophys. Res.*, 70:3819-3829, 1965.

25. Wehner, G. K., Rosenberg, D. L., Kenknight, C. E., "Investigation of Sputtering Effects on the Moon's Surface," Eighth Quarterly Status Rep. Contract NAS w-751, NASA and Litton Systems, Inc., Minneapolis, Minn., 1965.

26. Kozyrev, N., "Observation of a Volcanic Process on the Moon," *Sky and Telescope*, 18:184-186, 1958; translated by L. G. Jacchia.

27. Kozyrev, N., "Volcanic Phenomena on the Moon," *Nature*, 198:979-980, 1963.

28. Greenacre, A., "A Recent Observation of Lunar Color Phenomena," *Sky and Telescope*, 26:316-317, 1963.

29. Cameron, W. S., "An Interpretation of Schröter's Valley and Other Lunar Sinuous Rilles," *J. Geophys. Res.*, 69(12):2430-2432, 1964.

NASA-Langley, 1966